N62-14090

TECHNICAL NOTE

D-1349

THE DISTRIBUTION OF SMALL INTERPLANETARY DUST PARTICLES IN THE VICINITY OF THE EARTH

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SUMMARY

Existing direct measurements of small interplanetary dust particles in the vicinity of the earth are analyzed on the basis of new data obtained with the satellite Explorer VIII (1960ς). All but one of the direct measurements made with microphone systems on other spacecraft fit remarkably well on the distribution curve derived from Explorer VIII data. This agreement permits the construction of an average distribution curve for small interplanetary dust particles in the vicinity of the earth. The equation of a straight line segment that approximately fits this new distribution curve for particle masses between 10^{-10} and 10^{-6} gm is

$$\log I = -17.0 - 1.70 \log m$$

where I is the influx rate in particles/m²-sec and m is the mass in grams. One of the more important consequences of the new distribution curve is the evidence that the accretion of particulate matter by the earth is dominated by particles with characteristic dimensions of a few microns.

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INTRODUCTION

One of the components of the solar system is a cloud of dust particles surrounding the sun. Its importance arises not only from cosmogonal aspects, such as the sources and composition of the dust particles, but also from cosmological aspects, such as the rapidity of changes in the dynamical characteristics of the dust particles. Properties of these dust particles and the general shape and extent of the dust cloud have been inferred from observations of meteors and from photometric studies of the zodiacal light and the solar corona. Uncertainties arise in conclusions reached on the basis of such inferences, because of the differences that possibly exist between the classes of dust particles responsible for the two vastly different phenomena.

New and independent methods of determining selected parameters of the dust particles are needed to remove the present uncertainties concerning the physical characteristics and distributions of interplanetary dust particles. A new technique that holds great promise for supplying some of the most needed parameters of interplanetary dust particles has been developing very rapidly during the past few years. This technique consists of measuring (in space) various parameters of statistical samples of dust particles. The direct measurements that are presently available have been obtained as dust particles impacted on special sensors mounted on rockets, earth satellites, and other spacecraft. The dust particle sensors have necessarily been of very simple design and have provided only limited information about the dust particles. The experiments have been designed primarily to give preliminary information about the influx rate or spatial density of dust particles over a limited but astronomically important range of particle mass. More sophisticated experiments, capable of defining selected parameters of individual dust particles, will be technically feasible in the very near future.

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Radar, visual, and photographic techniques are used in observing meteoric phenomena produced by meteoroidal dust particles. The dust particles studied by means of the direct measurements technique are too small to produce meteoric phenomena and cannot be observed by the ground-based techniques common to studies of meteors. Some of the magnetic spherules found in deep sea deposits and in high altitude collections of atmospheric aerosols may include extraterrestrial material, but positive identification of this component is extremely difficult. Volatile cometary debris does not appear in either of the collections, and there has been little, if any, success in the identification of siliceous particles as being of extraterrestrial origin.

We are left with the conclusion that there are basically two effective techniques of experimentally acquiring reliable information about the distributions and physical characteristics of small interplanetary dust particles. The first technique is the photometric study of the zodiacal light and the solar corona (from outside the earth's atmosphere as well as from the surface). The second technique is to make statistical samples within the dust cloud by the direct measurements technique. This technique can include bringing collections of dust particles to the earth from outside the atmosphere as well as directly measuring selected parameters of dust particles in space. The two techniques must be complementary: Each technique should supply information unique to itself as well as information to be used in advancing the other technique.

Spacecraft carrying instruments for direct measurements can be used to probe comets and meteor streams and simultaneously to study the zodiacal dust cloud. Probes sent through comets and meteor streams would provide valuable information about the physical conditions and processes within such collections of dust particles. The direct measurements technique represents an interesting, useful, and almost unique means of studying small particulate aggregates of matter in selected regions of the solar system as well as in the vicinity of the earth.

INTERPRETATION OF DIRECT MEASUREMENTS

Available direct measurements must be reviewed periodically to determine how consistently they fit into a pattern that has physical meaning. Prior to the measurements obtained with Explorer VIII (1960ξ), the nature of the direct measurements was such that they could be given either of two interpretations regarding the average distribution of dust particles in the vicinity of the earth. The choice depended critically upon the assumptions made during an analysis of the data. The two interpretations were: (1) that the mass distribution and spatial density of small interplanetary dust particles indicated by direct measurements differ significantly from those predicted on the basis of linear extrapolations (over about six orders of magnitude) of results from the observations of meteors; or (2) that the direct measurements indicated the existence of an appreciable geocentric concentration of interplanetary dust particles. This conjectural geocentric concentration is of

the type proposed by Beard (Reference 1). It should not be confused with concentrations arising from the temporary suspension of dust particles above the temperature inversion layers in the earth's atmosphere.

The second of these two interpretations is not compatible with an analysis in which the direct measurements from Explorer VIII are used as a basis for analyzing other direct measurements. Therefore, the Explorer VIII measurements strongly indicate that the first interpretation is correct; and it should be so regarded, at least until direct measurements of the vectorial velocities of impacting dust particles, or direct measurements at large geocentric distances, have been obtained.

The direct measurements from Explorer VIII serve as the first firm basis for analyzing all existing direct measurements of interplanetary dust particles. A review of all the available direct measurements (including those from Explorer VIII) obtained with microphone systems is sufficient to demonstrate the validity of the foregoing statements about their interpretation.

DIRECT MEASUREMENTS FROM EXPLORER VIII

Two independent systems for studying interplanetary dust particles were mounted on Explorer VIII. These systems provided data from the date of launch, November 3, 1960, until the power supplies were exhausted, December 13, 1960. One of the systems employed a photomultiplier tube as the sensor for measuring the luminous energy generated by hypervelocity impacts of dust particles. A microphone was used as the sensor in the other system. It counted impacts and determined in which of three ranges lay the magnitude of the impulse delivered by an impacting dust particle.

The microphone system had two sounding boards, which were mounted on the lower cone of this spin-stabilized satellite. The spin vector of the satellite lay within approximately 40 degrees of the apex of the earth's motion during the active lifetime of the satellite. The sounding boards were arranged to detect dust particles for which the radiants generally lay on the hemisphere centered on the antapex of the earth's motion. An average particle velocity of 25 km/sec has been assigned to the dust particles that struck Explorer VIII, and is to be used until the velocity distribution of interplanetary dust particles can be determined.

The best calibrations presently possible for the microphone system show that it is sensitive to an impulse that is closely related to the momentum of an impacting dust particle. Calibrations have been accomplished through the use of low velocity particles impacting elastically on sounding boards to which the microphones were attached. Hypervelocity particle accelerators are presently being used in experiments to obtain more realistic calibrations of the microphone system. The mass sensitivity of a microphone

system can be computed from the momentum sensitivity if an average particle velocity is assigned.

The Explorer VIII microphone system was designed to count impacting dust particles and to determine in which of three ranges the momentum of each particle lay. A preliminary read-out of the data has progressed sufficiently far to establish approximately the number of dust particles encountered for each of the three ranges of sensitivity. In addition to determining the average influx rate within each of the ranges, the data have defined the shape of a section of an average mass distribution curve. This section extends over a limited but significant range of particle mass and provides a basis for analyzing all the other available direct measurements of interplanetary dust particles.

A tabulation of the preliminary data from Explorer VIII has not been included in this paper, to prevent unnecessary propagation of preliminary numerical results that may change slightly. However, the three data points obtained with the microphone system on Explorer VIII have been corrected for the effect of shielding by the earth and plotted as a cumulative mass distribution in Figure 1. These points represent the impacts of more than 3100 dust particles registered during an interval of 40 days. The large number of impacts provides statistical weight for the data points from the two ranges of highest sensitivity. The spacing of the threshold sensitivities allows definitive establishment of the shape of a segment of an average distribution curve extending over approximately three orders of magnitude in particle mass.

DIRECT MEASUREMENT FROM OTHER SATELLITES AND SPACECRAFT

Direct measurements have been obtained with rockets, earth satellites, and space probes flown by both the United States and the Soviet Union. Dust particle sensors carried by these payloads have included microphones, photomultiplier tubes, thin films, erosion grids, wire grids, and pressurized chambers. The microphone system is probably the best calibrated, and certainly has been flown more times and on more payloads than any other sensor.

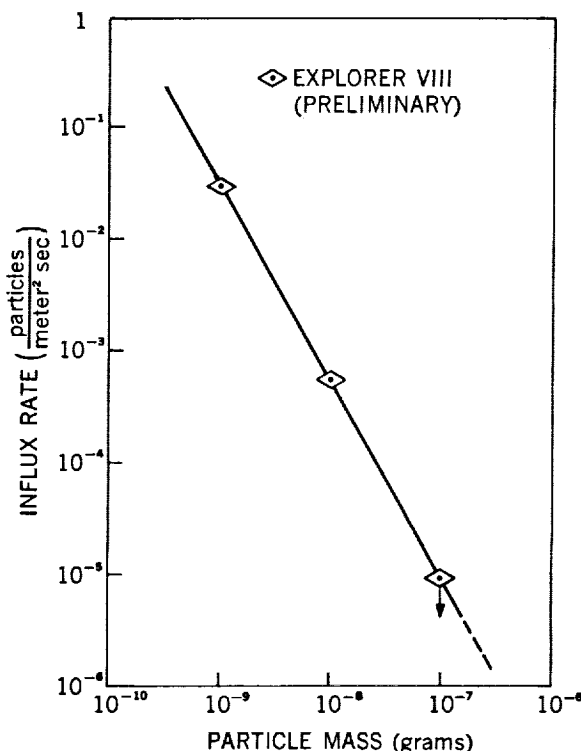It is sufficient, for the purposes of the analysis summarized in this paper, to

Figure 1 - The average distribution curve established by preliminary results from Explorer VIII

consider only those direct measurements obtained with microphone systems. These data are sufficient to establish an average distribution curve for interplanetary dust particles in the vicinity of the earth. And it may be qualitatively stated that the direct measurements obtained with other systems do not suggest a distribution curve different from the one established by the direct measurements obtained with microphone systems.

The U.S. spacecraft for which direct measurements with microphone systems have been obtained are listed in Table 1, together with data relevant to the systems. The data for Explorer I (1958α) and Pioneer I are those given by Dubin (Reference 2). The total number of impacts (145) for Explorer I was used in computing an average influx rate even though approximately half the impacts probably represent a "shower" component (Reference 3). (The high influx rate during the "shower" is approximately counteracted by an interval with a low influx rate.) An influx rate computed from the total number of impacts serves very well as the average influx rate for Explorer I and may be used in establishing the average distribution curve. A factor of 2 was used in correcting the Explorer I influx rate for the shielding effect of the earth.

The microphone system on Pioneer I registered 25 impacts. Of these, 17 probably represented dust particle impacts, and the cumulative influx rate measured by this vehicle was computed on that basis. No correction was made for the shielding effect of the earth because Pioneer I spent most of its time at a considerable distance from the earth.

Preliminary results for the microphone system on Vanguard III (1959η) were reported by LaGow and Alexander (Reference 4). Reading of the telemetered data from Vanguard III is still in progress, so the preliminary results shown in Table 1 may change slightly. Approximately 6000 impacts were recorded on Vanguard III during about 80 days of operation. Approximately 2800 of the impacts occurred during a 70 hour interval on November 16-18, 1959 (Reference 5). An average influx rate was computed for Vanguard III on the basis of 3500 impacts. This number includes an allowance for the sporadic background during the 70 hour interval. A factor of 1.5 was used to correct for the shielding effect of the earth. An average particle velocity of 30 km/sec was used in computing the threshold mass sensitivities for the microphone systems on all three spacecraft listed in Table 1.

Direct measurements reported by Nazarova (Reference 6) from the microphone systems mounted on Soviet spacecraft are included in Table 2. Also, portions of the information in Table 2 have been computed on the basis of Nazarova's information, in order that data from the U.S. and Soviet spacecraft could be included in the same analysis.

The sensitivities of the microphone systems on the Soviet spacecraft were expressed by Nazarova in terms of particle mass. She computed mass sensitivities by assuming that the microphone systems were energy sensitive and that the average particle velocity was 40 km/sec. McCracken (Reference 7) also used this value, in an early analysis of direct measurements, but it is almost certainly too high. Whipple (Reference 8) assigned

Table 1

Direct Measurements Obtained with Microphone Systems on U.S. Spacecraft

Spacecraft	Momentum Sensitivity (dyne sec)	Mass Sensitivity (gm)	Effective Area (m²)	Exposure Time (sec)	Exposure (m² sec)	Number of Particles	Cumulative Influx Rate ($\frac{\text{particles}}{\text{m}^2 \text{ sec}}$)	
							Observed	Corrected for Earth Shielding
Explorer I	$>2.5 \times 10^{-3}$	8.3×10^{-10}	2.3×10^{-1}	7.9×10^{4}	1.8×10^{4}	145	8.4×10^{-3}	1.7×10^{-2}
Pioneer I	$>1.5 \times 10^{-4}$	5.0×10^{-11}	3.9×10^{-2}	1.1×10^{5}	4.2×10^{3}	17	4.0×10^{-3}	$4.0 \times 10^{-3*}$
Vanguard III	$>1.0 \times 10^{-2}$	3.3×10^{-9}	4.0×10^{-1}	6.9×10^{6}	2.8×10^{6}	≈ 3500	1.3×10^{-3}	2.0×10^{-3}

*In this case the correction factor was unity

Table 2

Direct Measurements Obtained with Microphone Systems on Soviet Spacecraft

Spacecraft	Range of Mass Sensitivity (gm)		Effective Area (m²)	Exposure Time (sec)	Exposure (m² sec)	Number of Particles	Influx Rate ($\frac{\text{particles}}{\text{m}^2 \text{ sec}}$)	
	$\bar{v} = 40$ km/sec	$\bar{v} = 30$ km/sec					Nazarova	Cumulative
Sputnik III (1958δ)	$8.0 \times 10^{-9} - 2.7 \times 10^{-8}$ $2.7 \times 10^{-8} - 1.5 \times 10^{-7}$ $1.5 \times 10^{-7} - 5.6 \times 10^{-6}$ $>5.6 \times 10^{-6}$	$1.4 \times 10^{-8} - 4.8 \times 10^{-8}$ $4.8 \times 10^{-8} - 2.7 \times 10^{-7}$ $2.7 \times 10^{-7} - 1.0 \times 10^{-5}$ $>1.0 \times 10^{-5}$	0.34	$\approx 8 \times 10^{5}$	$\approx 3 \times 10^{5}$	?	(see text)	$<1 \times 10^{-4}$
Space Rocket I	$2.5 \times 10^{-9} - 1.5 \times 10^{-8}$ $1.5 \times 10^{-8} - 2.0 \times 10^{-7}$ $>2.0 \times 10^{-7}$	$4.4 \times 10^{-9} - 2.7 \times 10^{-8}$ $2.7 \times 10^{-8} - 3.6 \times 10^{-7}$ $>3.6 \times 10^{-7}$	0.2	3.6×10^{4}	7.2×10^{3}	<16 <4 <1	$<2 \times 10^{-3}$ $<5 \times 10^{-4}$ $<1 \times 10^{-4}$	$<2.9 \times 10^{-3}$ $<7.0 \times 10^{-4}$ $<1.4 \times 10^{-4}$
Space Rocket II	$2.0 \times 10^{-9} - 6.0 \times 10^{-9}$ $6.0 \times 10^{-9} - 1.5 \times 10^{-8}$ $>1.5 \times 10^{-8}$	$3.6 \times 10^{-9} - 1.1 \times 10^{-8}$ $1.1 \times 10^{-8} - 2.7 \times 10^{-8}$ $>2.7 \times 10^{-8}$	0.2	1.1×10^{5}	2.2×10^{4}	0 0 2	$<5 \times 10^{-5}$ $<5 \times 10^{-5}$ 9×10^{-5}	9.1×10^{-5}
Interplanetary Station (1959θ)	$1.0 \times 10^{-9} - 3.0 \times 10^{-9}$ $3.0 \times 10^{-9} - 8.0 \times 10^{-9}$ $>8.0 \times 10^{-9}$	$1.8 \times 10^{-9} - 5.3 \times 10^{-9}$ $5.3 \times 10^{-9} - 1.4 \times 10^{-8}$ $>1.4 \times 10^{-8}$	0.1	2.3×10^{4}	2.3×10^{3}	1 5 1	4×10^{-4} 2×10^{-3} 4×10^{-4}	3.0×10^{-3} 2.6×10^{-3} 4.3×10^{-4}

different values of average velocity to dust particles of different sizes. These velocities varied from 28 km/sec for meteoroids to 15 km/sec for small dust particles of the direct measurements range of particle size. In order to avoid prematurely constraining the model distribution of interplanetary dust particles, a value of 30 km/sec is here used as the average particle velocity when the spacecraft was not oriented or when the dust particle sensors were open to an omnidirectional flux of dust particles. Average particle velocities for oriented sensors have been chosen according to the orientation of the solid viewing angle of the sensor.

The mass sensitivities for the systems on the Soviet spacecraft have been reduced by the square of the ratio of 40 to 30 in order to compensate for the difference in the assigned average particle velocities. The Soviet spacecraft Space Rocket I (Lunik I or Mechta, launched January 2, 1959), Space Rocket II (Lunik II or Lunar Probe, launched September 12, 1959), and the Interplanetary Station (Lunik III or 1959θ) operated at moderately large geocentric distances, so corrections for the shielding effect of the earth are not necessary.

The influx rates measured by Sputnik III (1958 δ_2) changed tremendously during the first three days of operation of the equipment. The influx rates, as reported by Nazarova (Reference 6), were 4 to 11 particles/m^2 per second on May 15 (launch day), 5×10^{-4} particles/m^2 per second on May 16-17, and less than 10^{-4} particles/m^2 per second during the interval of May 18-26. Nazarova attributes the high influx rates during the first few days to a meteor shower, but the manner in which the influx rate changed could also be suggestive of payload interference. Only the influx rate for the last 9 days of operation is of any value in establishing an average distribution curve for Sputnik III. It is not clear whether Nazarova corrected the influx rate from Sputnik III for the shielding effect of the earth, so the influx rate for this satellite is left as given.

The method of encoding information into the telemetered signal for Space Rocket I was such that only very crude upper limits for the influx rates could be set. Only that influx rate measured by the scale of highest sensitivity is of any value in the present analysis.

DIRECT MEASUREMENTS FROM ROCKETS

Signals that could be ascribed to no other source than the impacts of dust particles onto the skins of rockets were first found on the telemetry records for two V-2 rockets. The rockets were V-2 Blossom IV-D and V-2 Blossom IV-G, flown on December 8, 1949, and August 31, 1950, respectively. Microphones and the associated electronics were designed and installed by personnel of Temple University under the direction of Professor J. L. Bohn. The equipment was flown to measure acoustical intensities in the warheads and on the skins of the rockets. Descriptions of the instrumentation and the data have been given in detail by Bohn and Nadig (Reference 9).

Bohn and Nadig tentatively advanced the suggestion that the unexplained pulses observed on the telemetry records were caused by the impacts of meteoric particles on the skins of the rockets. This explanation may now be regarded as the correct one. The data from these flights were the first direct measurements of interplanetary dust particles ever obtained. Both sets of data are regarded as being qualitatively fair but of no use in quantitative discussions of interplanetary dust particles.

Spare equipment from the V-2 flights was mounted on Aerobee No. 58 and flown on September 14, 1955 (Reference 10). This rocket did not reach a sufficiently high altitude to observe dust particles before they had been appreciably decelerated by atmospheric drag forces. Signals that probably were caused by dust particle impacts were recorded, but the data must be classified as only a qualitatively fair measurement.

Bohn and Nadig (Reference 9) also proposed that rockets be flown carrying special acoustical systems for counting dust particle impacts. Preferably, the rockets were to have nose tips that could be ejected in order to expose a circular diaphragm to the impacts. They also suggested that shielding the diaphragm during the rocket's passage through the lower atmosphere would eliminate the possibility of spurious counts being introduced by aerodynamic heating of the sensor. The type of rocket program that was suggested was carried further under the direction of Mr. M. Dubin, then of the Air Force Cambridge Research Center, who is responsible for the series of rockets discussed below.

Table 3 is a chronological list of the rockets that have carried microphone systems. Aerobee No. 77 was the first of a series of thirteen rockets instrumented with microphone systems and flown by Oklahoma State University (OSU) under contract with the Air Force. This series was flown especially for the purpose of directly measuring the influx rates and momenta of interplanetary dust particles. Aerobee No. 77, like the other Aerobees in the OSU series, had two crystal microphones mounted on the skin of the instrument compartment and two mounted on a circular diaphragm that could be exposed by ejecting the nose tip of the rocket at an altitude of about 60 km. But the rocket reached zenith at an altitude of 27 km, too low for proper operation of the microphone system. Its diaphragm had been highly polished by Bohn in the hope that hypervelocity craters would be found on it when recovered. The recovered diaphragm was examined photochemically by Yagoda (Reference 11) who found several tiny craters resembling those formed by hypervelocity impacts of small dust particles.

Seven of the series of thirteen rockets provided data that are of use in quantitative discussions of interplanetary dust particles. A preliminary read-out of the data from six of these rockets was included in an early analysis of direct measurements by McCracken (Reference 7). A final read-out of the uncorrected data from the seven rockets was made available as a final report on the OSU contract, dated April 14, 1960 (Reference

Table 3

Rockets Which Carried Microphone-Type Dust Particle Sensors

Rockets	Launch Time and Date		Zenith Altitude (km)	Type of Data
V-2 Blossom IV-D		Dec. 8, 1949	≈ 135	Qualitatively fair
V-2 Blossom IV-G		Aug. 31, 1950	≈ 135	Qualitatively fair
AEROBEE No. 58		Sept. 14, 1955	100	Qualitatively fair
AEROBEE No. 77	0819 MST	Apr. 9, 1957	27	None; vehicle failure
AEROBEE No. 80	0630 MST	July 16, 1957	122	Quantitatively good
AEROBEE No. 81	0730 MST	July 18, 1957		None; vehicle failure
AEROBEE No. 87	0808 MST	Oct. 14, 1957	146	None; telemetry difficulty
AEROBEE No. 88	2212 MST	Oct. 16, 1957	114	Quantitatively good
NIKE-CAJUN AF-1	0944 MST	Apr. 24, 1958	167	None; thermal interference
NIKE-CAJUN AF-2	0533 MST	May 1, 1958	137	Quantitatively fair
NIKE-CAJUN AA6.203	2200 CST	Oct. 15, 1958	151	Quantitatively good
NIKE-CAJUN AA6.204	0600 CST	Oct. 14, 1958	137	Quantitatively good
NIKE-CAJUN AA6.205	2125 CST	Oct. 17, 1958	143	None; mechanical failure
NIKE-CAJUN AA6.206	2145 CST	Oct. 21, 1958	157	Quantitatively fair
SPAEROBEE 10.01	1047 CST	Oct. 22, 1958	177	Quantitatively fair
SPAEROBEE 10.02	1327 CST	Oct. 25, 1958	420	None; telemetry failure

12). Data for the seven rockets are given in Table 4. Corrections have been applied for counts that possibly could have arisen from causes other than dust particle impacts. The data from Nike-Cajun AF-2 have been slightly rearranged in order to compensate for a change in sensitivity that occurred as a result of a low battery potential during the flight. A corrected tabulation of the data from the OSU rockets has not previously been made available in the open literature because of the series of corrections that were in progress and were only recently completed. More details of the rocket flights and a description of the procedures followed in reading out and correcting the data will be made available at a later time.

Only impacts which occurred when the rockets were at altitudes greater than 110 km have been counted. The deceleration of dust particles by atmospheric drag forces becomes quite appreciable at altitudes below about 100 km; the velocities of the dust particles become functions of altitude and zenith angle, making the determination of the particle velocities relative to a rocket an almost impossible task. Setting the lower limit on altitude at 110 km allows one to assume that the majority of the dust particles impacting on the sensors were not appreciably decelerated by atmospheric drag forces. Geocentric velocities of dust particles above the earth's atmosphere probably lie between 11 and 72

Table 4

Basic Corrected Data for the Successful OSU Rockets

Rocket	Range of Momentum Sensitivity (dyne sec)	Effective Area (m^2)	Time h $\geq$ 110 km (sec)	Exposure h $\geq$ 110 km (m^2 sec)	Number of Impacts
AEROBEE No. 80	$6.0 \times 10^{-4} - 3.0 \times 10^{-3}$ $3.0 \times 10^{-3} - 8.0 \times 10^{-3}$ $1.0 \times 10^{-3} - 3.0 \times 10^{-3}$ $3.0 \times 10^{-3} - 1.8 \times 10^{-2}$	0.05 0.05 0.5 0.5	100	5.0 5.0 50 50	39 10 2 1
AEROBEE No. 88	$1.3 \times 10^{-4} - 2.0 \times 10^{-3}$ $2.0 \times 10^{-3} - 2.6 \times 10^{-2}$ $4.7 \times 10^{-4} - 1.0 \times 10^{-3}$ $1.0 \times 10^{-3} - 2.8 \times 10^{-3}$	0.05 0.05 0.5 0.5	60	3.0 3.0 30 30	5 1 10 7
NIKE-CAJUN AF-2	$6.0 \times 10^{-4} - 1.2 \times 10^{-3}$ $1.2 \times 10^{-3} - 4.0 \times 10^{-3}$ $4.0 \times 10^{-3} - 3.0 \times 10^{-2}$	0.2	154	31	30 12 3
NIKE-CAJUN AA6.203	$3.0 \times 10^{-4} - 3.0 \times 10^{-3}$ $3.0 \times 10^{-3} - 1.8 \times 10^{-2}$	0.2	186	37	52 3
NIKE-CAJUN AA6.204	$7.0 \times 10^{-4} - 3.0 \times 10^{-3}$ $3.0 \times 10^{-3} - 3.0 \times 10^{-2}$	0.2	167	33	31 1
NIKE-CAJUN AA6.206	$1.5 \times 10^{-4} - 1.0 \times 10^{-3}$ $1.0 \times 10^{-3} - 6.0 \times 10^{-3}$ $7.0 \times 10^{-4} - 5.0 \times 10^{-3}$	0.2	118	24	11 1 6
SPAEROBEE 10.01	$5.0 \times 10^{-4} - 7.5 \times 10^{-3}$	0.04	202	8.1	20

km/sec, and if so, velocities of the dust particles relative to the rocket lie approximately between the same limits.

It seems reasonable to assign average particle velocities for each sensor of each rocket until the velocity distribution of the dust particles becomes known. Average particle velocities have been assigned on the basis of the region on the celestial sphere (relative to the apex of the earth's motion) to which the rocket sensors were exposed. The limiting mass sensitivity of each sensor has been computed from the momentum sensitivity and the assigned average particle velocity. Table 5 contains the limiting momentum sensitivities, the assigned average particle velocities, the limiting mass sensitivities, and the numbers of impacts from which data points for a cumulative mass distribution curve were computed.

The direct measurements made with the seven successful OSU rockets served as an early, preliminary determination of the influx rate and mass distribution of small interplanetary dust particles. The data were of considerable importance in the design of the dust particle experiments for the early satellites and space probes. The degree of importance may partially be illustrated by noting that the rocket data showed influx rates higher by a factor of 10^4 than was expected on the basis of an extrapolation of Watson's

tabulation (Reference 13) of the results from meteor observations, and higher by a factor of 10^2 than was expected on the basis of a similar extrapolation by Whipple (Reference 8). The weight and power allotments on the early satellites did not permit experimenters to build enough dynamic range into the electronics to allow for such uncertainties in the influx rate. It is interesting and perhaps of moderate quantitative value to note that the rocket data agree with and support the more definitive direct measurements that are now available from satellites. However, the rocket data probably should not be used as the decisive element in a critical test of the validity of a particular model of the distribution of dust particles in the vicinity of the earth.

ANALYSIS OF THE DIRECT MEASUREMENTS

The available direct measurements that have been obtained with microphone systems on the OSU rockets, other U.S. spacecraft, and Soviet spacecraft are plotted as a cumulative mass distribution in Figure 2. The various direct measurements, with the exception of those from Pioneer I, fit remarkably well onto the curve in Figure 2 regardless of the geocentric distance or the sensitivity at which a particular direct measurement was made. The departure of the Pioneer I direct measurement from the average distribution curve can easily be explained on the basis of the actual fluctuations in the influx rates as

Table 5
Direct Measurements Obtained with the OSU Rockets

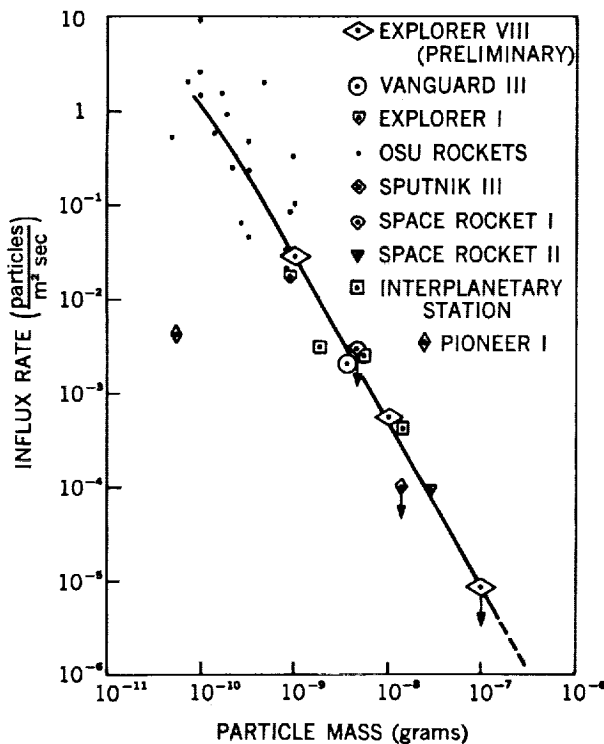| Rocket	Momentum Sensitivity (dyne sec)	Particle Velocity (km/sec)	Mass Sensitivity (gm)	Number of Impacts	Exposure $h \geq 100$ km (m^2 sec)	Cumulative Influx Rate $\left(\dfrac{\text{particles}}{m^2 \text{ sec}}\right)$
AEROBEE No. 80	$>6.0 \times 10^{-4}$ $>3.0 \times 10^{-3}$ $>1.0 \times 10^{-3}$ $>3.0 \times 10^{-3}$	70 70 40 40	$>8.6 \times 10^{-11}$ $>4.3 \times 10^{-10}$ $>2.5 \times 10^{-10}$ $>7.5 \times 10^{-10}$	49 10 3 1	5.0 5.0 50 50	9.8 2.0 6.0×10^{-2} 2.0×10^{-2}
AEROBEE No. 88	$>1.3 \times 10^{-4}$ $>2.0 \times 10^{-3}$ $>4.7 \times 10^{-4}$ $>1.0 \times 10^{-3}$	20 20 35 35	$>6.5 \times 10^{-11}$ $>1.0 \times 10^{-9}$ $>1.3 \times 10^{-10}$ $>2.9 \times 10^{-10}$	6 1 17 7	3.0 3.0 30 30	2.0 3.3×10^{-1} 5.7×10^{-1} 2.3×10^{-1}
NIKE-CAJUN AF-2	$>6.0 \times 10^{-4}$ $>1.2 \times 10^{-3}$ $>4.0 \times 10^{-3}$	40	$>1.5 \times 10^{-10}$ $>3.0 \times 10^{-10}$ $>1.0 \times 10^{-9}$	45 15 3	31	1.5 4.8×10^{-1} 9.7×10^{-2}
NIKE-CAJUN AA6.203	$>3.0 \times 10^{-4}$ $>3.0 \times 10^{-3}$	35	$>8.6 \times 10^{-11}$ $>8.6 \times 10^{-10}$	55 3	37	1.5 8.1×10^{-2}
NIKE-CAJUN AA6.204	$>7.0 \times 10^{-4}$ $>3.0 \times 10^{-3}$	40	$>1.8 \times 10^{-10}$ $>7.5 \times 10^{-10}$	32 1	33	9.7×10^{-1} 3.0×10^{-2}
NIKE-CAJUN AA6.206	$>1.5 \times 10^{-4}$ $>1.0 \times 10^{-3}$ $>7.0 \times 10^{-4}$	35	$>4.3 \times 10^{-11}$ $>2.9 \times 10^{-10}$ $>2.0 \times 10^{-10}$	12 1 6	24	5.0×10^{-1} 4.2×10^{-2} 2.5×10^{-1}
SPAEROBEE 10.01	$>5.0 \times 10^{-4}$	60	$>8.3 \times 10^{-11}$	20	8.1	2.5

Figure 2 — Average distribution curve established by direct measurements from microphone systems for interplanetary dust particles in the vicinity of the earth (cf. Figure 1)

measured with Explorer I, Vanguard III, and Explorer VIII — Pioneer I was active for about 1.5 days and easily could have flown during an interval of low dust particle activity.

The direct measurements listed in Tables 1, 2, and 5 encompass a variety of altitudes, sensitivities, lengths of sampling intervals, and times of the year. The fact that all except the direct measurements from Pioneer I fit the distribution curve established by Explorer VIII lends substantial support to the validity of the distribution curve shown in Figure 2 as an average distribution curve — to be used until more sophisticated experiments have established the distribution curve over a considerably larger range of particle mass.

Uncertainties are encountered in displaying the direct measurements as mass distributions. It is quite advantageous to the present analysis to point out these uncertainties. Qualitative discussions of the uncertainties will be followed by attempts to assign numerical values to them.

The values of average particle velocity assigned in converting from momentum sensitivity to mass sensitivity for the systems may be slightly too high. The correct values depend on the velocity distribution that exists for dust particles in the direct measurements range of particle size. Lower average particle velocities would apply if most of the dust particles were in geocentric orbits or direct, circular heliocentric orbits. The use of lower particle velocities would tend to shift the direct measurements of particle mass toward slightly higher values without markedly changing the shape of the distribution curve. Even a radical reduction from about 30 km/sec to the value 15 km/sec used by Whipple would lower the threshold mass sensitivities by only a factor of 2.

The impulse delivered to a sensor as a dust particle impacts at hypervelocity is almost certainly greater than the impact momentum of the dust particle, but it still remains unknown. A correction factor greater than unity (unity is used in Tables 1, 2, 4, and 5) for the ratio of the impulse to the impact momentum increases the values of momentum

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sensitivities for microphone systems. The proper correction factors probably lie be-
tween 2 and 3 and are now being established by hypervelocity accelerators.

If allowance is made for impacts of dust particles at angles of incidence appreciably
different from 0 degrees the momentum sensitivity effectively decreases, but the decrease
is probably by less than a factor of 2. This uncertainty can be largely removed through
the use of more directional sensors.

The magnitude of the correction for the shielding effect of the earth depends on the
velocity distribution of the dust particles. The corrections that have been applied involve
the assumption that the dust particles are predominantly in heliocentric orbits and are not
necessarily confined to direct, circular orbits. If this assumption is not valid, then slightly
smaller corrections for the shielding effect of the earth should be applied. The factors
applied to correct for the earth's shielding of the spacecraft are all less than or equal to
2. The use of smaller correction factors would shift the direct measurements toward
slightly lower values of influx rate without changing the shape of the distribution curve.

Knowing which of the minor corrections to apply requires a better knowledge than ex-
ists at present of the mass distribution, velocity distribution, and spatial density of inter-
planetary dust particles. All the direct measurements have been handled in as consistent
a manner as possible, so that the introduction of minor corrections, although changing the
position of the direct measurements on a plot of mass distributions, will not alter the shape
of the distribution curve. It seems reasonable to assume that likely combinations of the
minor corrections will leave the distribution curve as shown in Figure 2. Direct measure-
ments obtained at large distances from the earth, or a determination of the dust particle
velocity distribution, or both, are needed before much further progress can be made in de-
fining a model distribution of interplanetary dust particles.

The distribution curve shown in Figure 2 can be approximated reasonably well by a
straight line segment. Its equation is

$$\log I = -17.0 - 1.70 \log m$$

where I is the influx rate in particles/m^2 per second and m is the particle mass in grams
(Reference 15). The equation should not be used outside the range between 10^{-10} and 10^{-6}
gm. It is applicable for an average particle velocity of 30 km/sec.

The curve in Figure 2 is intended to be an average distribution curve for dust particles
in the vicinity of the earth; whether the distribution is the same in interplanetary space as
near the earth is a question that cannot yet be answered. If an appreciable concentration
exists near the earth as opposed to the amount at a distance from the earth, then the influx
rates measured at comparable sensitivities but at different geocentric distances should

have been functions of the geocentric distance. The influx rates measured at large geocentric distances (e.g., Space Rocket II, 3.6×10^5 km; Interplanetary Station, 4.7×10^5 km) should fall appreciably below those from Explorer VIII. And the low altitude (≈ 150 km) rockets should have shown influx rates considerably higher than those obtained with Explorer VIII. But, with the exception of the direct measurements from Pioneer I, the departures of direct measurements from the distribution curve established by Explorer VIII are negligible.

The distribution curve of Figure 2 is shown together with curves of the model distribution of meteors as taken from Watson (Reference 13), and Whipple (References 8 and 15), in Figure 3. None of the linear extrapolations of the results from meteor observations fits the direct measurements. The curves labeled "Watson (1941)" and "Whipple (1957)" approximately represent limits for the uncertainty encountered in placing influx rates for meteors on a mass distribution curve. The uncertainty of about 200 arises because the mass-to-magnitude relationships for meteors are not well known. This uncertainty exceeds by one to two orders of magnitude the uncertainties that exist for the direct measurements. The curve labeled "Whipple (1960)" represents a revision, by Whipple, of the curve labeled "Whipple (1957)". It was made in an attempt to remove the discrepancy between the linearly extrapolated meteor curves and the direct measurements.
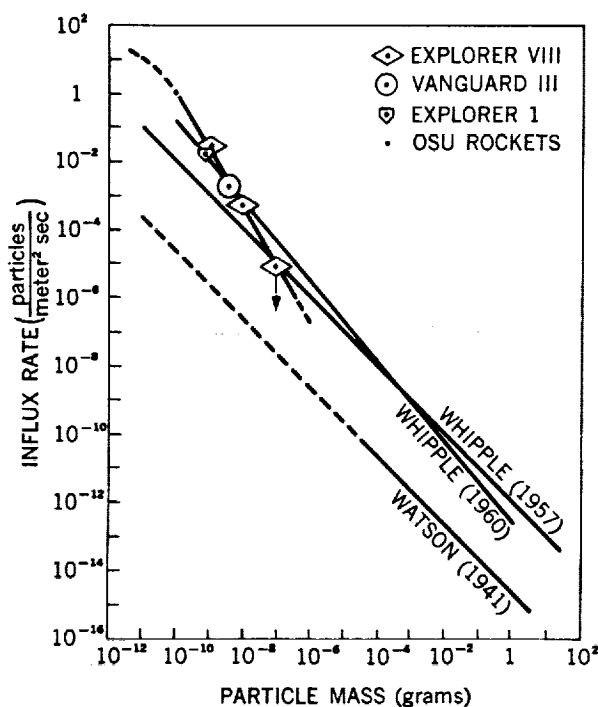
Figure 3 — Comparison of model distribution curves obtained from direct measurements and from extrapolations of results from meteor observations

Whipple (References 15, 16, and 17) performed an analysis of the direct measurements and concluded that: "Acoustical impacts of meteoritic dust on counting devices that are carried by satellites and space probes show clearly that a high concentration of interplanetary dust occurs near the earth" (Reference 17). In his analysis, Whipple used the departures of the direct measurements from the curve labeled "Whipple (1960)" in Figure 3 to show that the geocentric concentration of dust particles varied inversely as the 1.4 power of distance from the earth's surface. Interpretation of the direct measurements in such a manner that they indicate the existence of a geocentric concentration represents the second of the two interpretations mentioned earlier

that were possible before the Explorer VIII direct measurements. But Whipple's approach to analyzing the direct measurements is incompatible with the new direct measurements from Explorer VIII.

The following paragraphs outline arguments that may be advanced against the claim that the direct measurements confirm the existence of a geocentric concentration of dust particles.

The data points representing the largest numbers of impacts (Explorer VIII, Vanguard III, Explorer I, OSU Rockets) fit the same straight line segment (Figure 2) regardless of the altitude at which a particular direct measurement was obtained.

Allowance must be made for the differences in sensitivities of the various microphone systems before a comparison can be made between influx rates to see if an altitude dependence exists. This requires normalizing all the direct measurements to a given value of particle mass. The distribution curve used as the normalization standard is *extremely* critical to the interpretation of the direct measurements. The use of the conjectural curve labeled "Whipple (1960)" as the normalization standard leads to the conclusion that the direct measurements indicate a geocentric concentration. But the empirical distribution curve established by Explorer VIII gives no discernible evidence from the direct measurements that such a geocentric concentration of dust particles exists.

The slopes of straight line segments of the distribution curve shown in Figure 2 as separately indicated by each of the three groups of direct measurements (OSU rockets, other U.S. spacecraft, and Soviet spacecraft) are between -1.5 and -2.0. These values differ significantly from the value of approximately -1.2 used by Whipple (Reference 15) to normalize the direct measurements in such a manner that a geocentric concentration would be evident.

The most critical data points in Whipple's analysis are the direct measurements of the OSU rockets and Explorer VI (1959δ). It should be pointed out that in adjusting the sensitivities of the systems on the rockets, Whipple introduced an error of about 15 in the influx rate. Also, the Explorer VI experimenters have not placed their data into the open literature, so these data should not be used as a critical point yet.

CONCLUSIONS

Several interesting conclusions can be reached on the basis of the new distribution curve established by the direct measurements of interplanetary dust particles. Some of the more important ones follow.

The average distribution curve established by direct measurements can be approximately represented over the range of mass between 10^{-10} and 10^{-6} gm by a straight line segment whose equation is

$$\log I = -17.0 - 1.70 \log m$$

where I is the omnidirectional influx rate in particles/m² per second and m is the mass.

Particulate aggregates of matter accreted by the earth consist primarily of dust particles smaller than the faintest radar meteors, the accretion rate being approximately 10^4 tons per day on the earth. This rate is in good agreement with an earlier estimate (Reference 18) based on the direct measurements from Explorer I.

The convenient constant-mass-per-magnitude relationship common to discussions of results from meteor observations does not hold for dust particles in the direct measurements range of particle mass. The distribution curve established by direct measurements departs markedly from distribution curves obtained by linearly extrapolating the results from meteor observations.

Available direct measurements extend almost into the range of particle mass where radiation pressure control is important. A rather marked change in the shape of the distribution curve should occur, as a result of radiation pressure, at values of particle mass slightly lower than those presently covered by the direct measurements.

The distribution curve established by direct measurements can be joined to a model constant-mass-per-magnitude curve for meteors within the range of particle size typical of the faint radar meteors. Such a junction probably has and will continue to have little physical meaning until the mass-to-magnitude relationship for meteors can be established, or until statistically significant direct measurements can be obtained in the range of particle mass between 10^{-7} and 10^{-5} gm.

The presently available direct measurements show (within themselves) no discernible evidence for the existence of an appreciable geocentric concentration of interplanetary dust particles. If a geocentric concentration does exist, then its existence can be reliably inferred from the type of direct measurement that is presently available only if future direct measurements obtained at large geocentric distances deviate appreciably from the average distribution curve shown in Figure 2.

The distribution curve in Figure 2 can only be used to describe average conditions. It is already known from the direct measurements that fluctuations of at least ± 10 in the influx rate occur within intervals of a few hours for particles with masses of approximately 10^{-10} gm (Reference 19). The magnitude of the fluctuations presumably becomes quite large for particles near the radiation pressure limit on particle size. The distribution

curve is slightly biased toward the latter part of the year because of the dependence of the distribution of direct measurements on the time of year. If the annual variation in the influx rate of dust particles resembles that of meteors, then the curve shown in Figure 2 represents influx rates slightly higher than the true average values.

Large inconsistencies have been attributed to the direct measurements several times (References 20 and 21). But the various direct measurements seem to be remarkably self-consistent when analyzed on the basis of the new direct measurements from Explorer VIII. The authors place much confidence on the direct measurements from Explorer VIII. The reliability and calibration of the Explorer VIII data and the reasons for assigning a high level of confidence to them will be presented in greater detail in a future publication.

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NASA TN D-1349
National Aeronautics and Space Administration.
THE DISTRIBUTION OF SMALL INTERPLANETARY
DUST PARTICLES IN THE VICINITY OF THE
EARTH. C. W. McCracken and W. M. Alexander.
July 1962. 18p. OTS price, $0.50.
(NASA TECHNICAL NOTE D-1349)

Existing direct measurements of small interplanetary
dust particles in the vicinity of the earth are analyzed
on the basis of new data obtained with the satellite
Explorer VIII (1960ξ). All but one of the direct meas-
urements made with microphone systems on other
spacecraft fit remarkably well on the distribution
curve derived from Explorer VIII data. This agree-
ment permits the construction of an average distribu-
tion curve for small interplanetary dust particles in
the vicinity of the earth. The equation of a straight
line segment that approximately fits this new distribu-
tion curve for particle masses between 10-10 and
10-6 gm is

$$\log I = -17.0 - 1.70 \log m$$

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II. Alexander, W. M.
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(Initial NASA distribution:
7, Astrophysics;
16, Cosmochemistry;
21, Geophysics and
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where I is the influx rate in particles/m^2-sec and m is the mass in grams. One of the more important consequences of the new distribution curve is the evidence that the accretion of particulate matter by the earth is dominated by particles with characteristic dimensions of a few microns.

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